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In the initial phases, we showed that we can prepare self-supporting masks and that the concept of magnetic stabilization using exchange bias is feasible. We developed instrumentation for the preparation of porous alumina masks on a substrate and automated analysis methods for characterization of dot distribution. During the next phase, we started preparation and characterization of samples grown on Si substrates. Studies of the magnetic properties were started during the third phase. Further studies are needed to reach the terrabit-per-square inch goal.

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FINAL REPORT
June 1, 2001-November 30, 2003

Nanostructured Magnetism for Super-Dense Memories
AFOSR – F49620-01-1-0393

(AWARD # FOR NEW GRANT PERIOD: FA9550-04-1-0160)

Prof. Ivan K. Schuller, P.I.
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La Jolla, CA 92093

1. OBJECTIVES

This proposal has been dedicated to the development of nanostructured medium for super-dense memory architecture. More specifically, we concentrated on the preparation, characterization and the study of the physical limitations of artificially nanostructured magnetic materials. These materials will be the building blocks for future ultra-high density patterned magnetic storage media. Under this project we developed self-assembly and electron beam lithography methods for the preparation of nanostructured magnetic arrays, characterize their physical and chemical properties quantitatively and solve the limitation imposed by the superparamagnetic limit.

2. STATUS OF EFFORT

In the initial phases, we showed that we can prepare self-supporting masks and that the concept of magnetic stabilization using exchange bias is feasible. We developed instrumentation for the preparation of porous alumina masks on a substrate and automated analysis methods for characterization of dot distribution. During the next phase, we started preparation and characterization of samples grown on Si substrates. Studies of the magnetic properties were started during the third phase. Further studies are needed to reach the terrabit-per-square inch goal.

3. ACCOMPLISHMENTS/NEW FINDINGS

The key for the development of super dense memories is the reproducible preparation of regular arrays of small (~100-200 Å) magnetic structures over macroscopic (cmxcm) areas on a substrate.

We have performed studies of the distribution and thermal stability of arrays of small (down to ~350 Å) magnetic dots on Si substrates using self assembled alumina as masks. We are able to prepare these arrays of nanodots over macroscopic (cmxcm) areas. The size and distribution of the mask and the arrays correlate well. The distribution width on the mask and array is of the order 10% so further improvements are needed. Improvements in the preparation of the alumina process are underway to decrease the size, to improve uniformity and to perfect array distribution. Further studies of the magnetic properties in an exchange biased and normal configuration are needed.

We are now concentrating on understanding the magnetic behavior of the dots we already prepared. Interestingly, we find below ~ 600 Å dot size a transition from single or multi- domain to vortex state to single domain with decreasing size. For Fe dots we find an unexpected exchange bias even for the dot arrays without an antiferromagnet deliberately added to the structure. We suspect that this "bonus" comes from a possible Fe oxide present, which provides the exchange bias. This is under investigation at the present time and needs further research.

To date the smallest sizes we can reproducibly prepare are close to 350Å with ~10% dispersion. Improvements in the preparation of the alumina process are underway to decrease the size, to improve uniformity and to perfect array distribution. Further studies of the magnetic properties in an exchange biased and normal configuration are needed.

4. PERSONNEL SUPPORTED

Postdoctoral Fellows:
Igor Roshchin
Maribel Montero
Johannes Eisenmenger (funded by von Humboldt foundation)

Graduate students:
Changpeng Li

Undergraduate Students:
Doug Bird
Nate Goldman (funded by NSF-REU program)

Visitors:
Waldemar Macedo (funded by Brazilian Government)
Jose Vicent (funded by Spanish sources)

Collaborators:

Kai Liu	O.M. Stoll	A. Hoffmann
Johan J. Åkerman	J.I. Martin	J.L. Vicent
S.M. Baker	T.P. Russell	C. Leighton
J. Nogues	J. Guimpel	H. Masuda
K. Nishio	S. M. Baker	M. Tuominen
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J.B. Kortright	T.C. Schulthess	S.K. Sinha
M.F. Toney	D. Weller	S. Wolf

5. PUBLICATIONS

Papers
Published in Refereed Journals

1. **Nanostructures and Proximity Effect**
M.I. Montero, Kai Liu, O.M. Stoll, A. Hoffmann, Ivan K. Schuller, Johan J. Åkerman, J.I. Martin, J.L. Vicent, S.M. Baker, T.P. Russell, C. Leighton and J. Nogues
J. Phys. D 35, 1 (2002).

2. **Hysteresis and Fractional Matching in Thin Nb Films with Rectangular Arrays of Nanoscaled Magnetic Dots**
O.M. Stoll, M.I. Montero, J. Guimpel, Johan J. Åkerman and Ivan K. Schuller
Phys. Rev. B 65, 104518 (2002).

3. **Fabrication and Thermal Stability of Arrays of Fe Nanodots**
Kai Liu, J. Nogues, C. Leighton, I.V. Roshchin, H. Masuda, K. Nishio, and Ivan K. Schuller
Appl. Phys. Lett. 81, 4434, (2002).

4. **Exchange Biased Magnetic Nanostructures**
Kai Liu, J. Nogués, C. Leighton, Ivan K. Schuller, S. M. Baker, M. Tuominen, T. P. Russell, H.Masuda, and K. Nishio,
Magnetoelectronics and Superconducting Electrical Engineering Conference, Beijing, China, August 10-15, 2002 – Proceedings.

5. **Ordered Magnetic Nanostructures: Fabrication and Properties**
J.I. Martin, J. Nogues, Kai Liu, J.L. Vicent and Ivan K. Schuller
Jour. Mag. Mag. Mat. 256, 449 (2003).

6. **Origin of Temperature Dependence in Tunneling Magnetoresistance**
Johan J. Åkerman, Igor V. Roshchin, J.M. Slaughter, Renu Whig Dave and Ivan K. Schuller
Europhys. Lett. 63 104 (2003).

7. **Relaxation Times in Exchange-biased Nanostructures**
Jose Mejia-Lopez, Dora Altbir and Ivan K. Schuller
Appl. Phys. Lett. 83, 332 (2003).

Papers Submitted to Refereed Journals (Not Yet Published)

1. **Neutron Scattering Studies of Nanomagnetism and Artificially Structured Materials**
M.R. Fitzsimmons, S.D. Bader, J.A. Borchers, G.P. Felcher, J.K. Furdyna, A. Hoffmann, J.B. Kortright, Ivan K. Schuller, T.C. Schulthess, S.K. Sinha, M.F. Toney D. Weller and S. Wolf
Jour. Mag. Mag. Mat. (In Press).

Invited Talks (At National and International Meetings)

1. **Magnetic and Superconducting Nanostructures**
Ivan K. Schuller
Festkolloquium, "Solid State Physics: Origin of the Future Electronics"
Tuebingen, Germany, October 19, 2001.

2. **Nanolithography Using Electron Beam Writing and Self Assembly**
Ivan K. Schuller, M.I. Montero, O.M. Stoll, Kai Liu and Johan J. Åkerman
Materials Research Society, Fall 2001 Meeting
Boston, MA November 26-30, 2001.

3. **Nanostructures,**
Ivan K. Schuller
Simposio en Fisica de Materiales del CCMC, Ensenada,
Mexico, January 23-26, 2002.

4. **Proximity Effect with Magnetic Nanostructures**
Ivan K. Schuller, O. Stoll, J. Akerman, J. Martin, K. Liu, C. Leighton, J. Nogues, J. Vicent, S.M. Baker, M. Tuominen and T.P. Russell
International Conference on Superconductivity, GMR & Related Materials: Novel Trends, Giens, France, June 1-8, 2002.

5. **Unusual Properties in Exchange Biased Bilayers**
J. Nogues, C. Leighton, M. Fitzsimmons, A. Hoffmann, K. Liu, M. Pechan, I.N. Krivorotov, E.D. Dahlberg and Ivan K. Schuller
IUMRS International Conference on Electronic Materials
Xian, China, June 10-14, 2002.

6. **Proximity Effect and Magnetic Nanostructures**
M.I. Montero, Kai Liu, O.M. Stoll, A. Hoffmann,, Johan J. Åkerman, J.I. Martin, J.L. Vicent, S.M. Baker, T.P. Russell, C. Leighton, J. Nogues and Ivan K. Schuller
TNT 2002 Conference, Santiago de Compostela (Spain), September 9-13, 2002.

7. **Adler Award Lecture: 25 Years of Metallic Superlattices**
Ivan K. Schuller
Bull. Am. Phys. Soc. 48, 137 (2003).

8. **Nanostructures: A Voyage from Three to Zero Dimensions**
Ivan K. Schuller, M. Montero, I. V. Roshchin, J.I. Martin, M. Velez, J. Nogues, A. Hoffmann, P. Prieto, J. Vicent, O. Stoll, Kai Liu, S.M. Baker, T.P. Russell, C. Leighton, H. Masuda, and K. Nishio
Institute for Structural and Engineering Materials (ISEM), Nagoya, Japan, June 24, 2003.

9. **Stabilization of Magnetism in Ferromagnetic Dot Arrays Towards Terrabit per Square Inch Storage**
Igor V.Roshchin, C.P. Li, M. Viret, Kai Liu, J.J. Tores, A.H. Romero, K. Nishio, H. Masuda, and Ivan K. Schuller, Non-Volatile Memory Technology Symposium NVMTS 2003, San Diego, CA., November 12-13, 2003.

Invited Talks at Research Institutions

1. **Artificially Prepared Nanostructures**
Ivan K. Schuller, University Ulm, October 17, 2001.

2. **Magnetic Nanostructures**
Ivan K. Schuller, UCSD Chemistry Department, January 29, 2002.

3. **Magnetic Nanostructures,**
Ivan K. Schuller, UCLA Physics Department Seminar, January 30, 2002.

4. **Fabrication and Magnetism of Nanodots and Wires with Nanoconstrictions.**
Igor V. Roshchin
Special Condensed Matter Seminar. University of Illinois at Urbana-Champaign. March 25 2002.

5. **Nanostructures and the Proximity Effect,**
Ivan K. Schuller, Technische Hochschule, Aachen, June 17, 2002.

6. **Nanostructures and Proximity Effect**
Ivan K. Schuller, Physics Department Colloquium, Ruhr-Universitat Bochum, July 8, 2002.

7. **Tunneling Criteria for Magnetic Tunnel Junctions**
Ivan K. Schuller, Dept. Fisica Fonamental, Univ. Barcelona, July 12, 2002.

8. **Nanostructures and the Proximity Effect**
Ivan K. Schuller, Hamburg University, Hamburg, Germany, August 2, 2002.

9. **Magnetism in Nanostructures**
Igor Roshchin
Division Seminar, General Physics , Institute of Russian Academy of Sciences, Moscow, Russia, October 2, 2002.

10. **Nanotechnology and Magnetism**
Igor Roshchin
Special Interdepartmental Colloquium,
Southern Ural State University, Chelyabinsk, Russia, October 8, 2002.

Contributed Talks

1. **Exchange Bias in Magnetic Nanostructures Over Macroscopic Area**
Kai Liu, Ivan K. Schuller, S.M. Baker, and T. Russell
8th Joint MMM-Intermag Conference, San Antonio, Texas, January 7-11, 2001.

2. **Tailoring Exchange Bias with Magnetic Nanostructures**
Kai Liu, Ivan K. Schuller, S.M. Baker, M. Tuominen, and T.P. Russell
Bull. Am. Phys. Soc. 46, 261 (2001).

3. **Magnetization Stabilization in Arrays of Fe Nanodots with Exchange Bias**
Kai Liu, J. Nogués, C. Leighton, H. Masuda, K. Nishio, and Ivan K. Schuller
Magnetism and Magnetic Materials Conference, Seattle, WA., November 13-16, 2001.

4 **Fabrication and Magnetization Stabilization in Arrays of Fe Nanodots with Exchange Bias**
Kai Liu, Igor V. Roshchin, Ivan K. Schuller, J. Nogues, C. Leighton, C. Londergan, C. Kubiak, K. Nishio, and H. Masuda
Bull. Am. Phys. Soc. 47, 789 (2002).

5. **Preparation of Nanoscopic Magnetic Structures in Exchange Biased Systems**
Sarah Olmstead, Shenda Baker, Ivan Schuller, Kai Liu, and Thomas P. Russell
Bull. Am. Phys. Soc. 47, 220 (2002).

6. **Exchange Biased Magnetic Nanostructures**
Kai Liu, J. Nogues, C. Leighton, Ivan K. Schuller, S.M. Baker, M. Tuominen, T.P. Russell, H. Masuda and K. Nishio
2002 International Symposium on Magnetoelectronics and Superconducting Electrical Engineering, Beijing, China, August 15-18, 2002.

7. **Magnetization Stabilization in Arrays of Fe Nanodots with Exchange Bias**
Igor V. Roshchin, C.P. Li, Kai Liu, K. Nishio, H. Masuda and Ivan K. Schuller
Bull. Am. Phys. Soc. 48, 1273 (2003).

8. **Synthesis and Thermal Stability of Nanomagnets**
Kai Liu, L. Zhao, P. Klavins, Frank E. Osterloh, J. Nogues, C. Leighton, H. Masuda, K. Nishio, I.V. Roshchin and Ivan K. Schuller, International Conference on Composites/Nano Engineering (ICCE), New Orleans, LA, July 20-26, 2003.

9. **Size Effects in Exchange Biased Nanostructures**
Johannes Eisenmenger, Zhipan Li, Oleg Petracic, Igor Roschin, Changpeng Li, Kai Liu, J. Nogués, C. Leighton, H. Masuda, K. Nishio, and Ivan K. Schuller
TNT 2003 "Trends in Nanotechnology", Salamanca, Spain, September 15-19, 2003.

6. HONORS AND AWARDS

Ivan K. Schuller

2003 – American Physical Society Adler Award – "For research in metallic heterostructures and superlattices, communicated with unusual enthusiasm and eloquence".

2003 – Materials Research Society - MRS Medal – "For innovative studies of exchange bias in magnetic heterostructures and nanostructures".